

Ultraluminous X-ray Sources and Star Formation

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ABSTRACT

Chandra observations of the Cartwheel galaxy reveal a population of ultraluminous X-ray sources (ULXs) with lifetimes $\lesssim 10^7$ yr associated with a spreading wave of star formation which began some 3×10^8 yr ago. A population of high-mass X-ray binaries provides a simple model: donor stars of initial masses $M_2 \gtrsim 15M_\odot$ transfer mass on their thermal timescales to black holes of masses $M_1 \gtrsim 10M_\odot$.

For alternative explanations of the Cartwheel ULX population in terms of intermediate-mass black holes (IMBH) accreting from massive stars, the inferred production rate $\gtrsim 10^{-6}$ yr $^{-1}$ implies at least 300 IMBHs, and more probably 3×10^4 , within the star-forming ring. These estimates are increased by factors η^{-1} if the efficiency η with which IMBHs find companions of $\gtrsim 15M_\odot$ within 10^7 yr is < 1 . Current models of IMBH production would require a very large mass ($\gtrsim 10^{10}M_\odot$) of stars to have formed new clusters. Further, the accretion efficiency must be low ($\lesssim 6 \times 10^{-3}$) for IMBH binaries, suggesting super-Eddington accretion, even though intermediate black hole masses are invoked with the purpose of avoiding it.

These arguments suggest either that to make a ULX, an IMBH must accrete from some as yet unknown non-stellar mass reservoir with very specific properties, or that most if not all ULXs in star-forming galaxies are high-mass X-ray binaries.

Key words: accretion, accretion discs – black hole physics – X-rays: binaries – stars: formation – galaxies: starburst

1 INTRODUCTION

Recent observations of external galaxies have uncovered a population of ultraluminous X-ray sources (ULXs: see Makishima et al., 2000 and references therein) with apparent luminosities well above the Eddington limit L_{Edd} for a stellar-mass black hole (or neutron star). Several authors have suggested that ULXs reveal accretion on to intermediate-mass black holes (IMBH), with masses between stellar values and the $> 10^6M_\odot$ inferred for active galactic nuclei (e.g. Colbert & Mushotzky, 1999; Ebisuzaki et al., 2001).

An alternative view (King et al., 2001) holds that ULXs are a bright, shortlived, but common phase of stellar-mass X-ray binary evolution. There is observational support for this, as Grimm, Gilfanov & Sunyaev (2002; see Table 1) show that apparently super-Eddington episodes are not uncommon in stellar-mass binaries. For example the high-mass system V4641 Sgr had a luminosity in the *Chandra* X-ray band of 3.3×10^{39} erg s $^{-1}$, despite a measured black hole mass of $9.6M_\odot$. The high apparent luminosities of the ULXs may either result from viewing a significantly anisotropic radiation pattern at a favourable angle, or be genuinely super-Eddington (cf Shaviv 1998, 2000; Begelman, 2002) or both. This form of ‘beaming’ need not involve relativistic effects, although Markoff et al., (2001) and Koerding et al. (2002)

have suggested that Doppler boosting in a relativistic jet could explain the high luminosities of ULXs.

A major clue to the nature of ULXs comes from the discovery of 7 ULXs in *Chandra* observations of the Antennae (Fabbiano et al., 2001). These strongly indicate a connection with recent massive star formation. IMBH models for ULXs (Miller & Hamilton, 2002; Gürkan, Freitag & Rasio, 2003) incorporate this by considering dense star clusters. These provide promising sites both for IMBH formation, and for capturing stellar companions to provide the accretion source. The X-ray binary picture (King et al., 2001) has a natural connection with massive star formation since it invokes a phase of high-mass X-ray (HMXB) binary evolution. This is the thermal-timescale mass transfer that must follow the familiar wind-fed HMXB phase, as is probably seen in SS433 (King, Taam & Begelman, 2000). (Note that ULXs are also seen in elliptical galaxies; in the X-ray binary picture these are bright, long-lasting outbursts of soft X-ray transients such as GRS 1915+105, cf King, 2002.)

The spectacular recent *Chandra* observation of the Cartwheel galaxy (Gao et al., 2003) gives the most graphic illustration so far of the connection between ULXs and star formation. The Cartwheel is well known as a site of recent massive star formation. Most of this is in a crisp ring ex-

panding about the point where an intruder galaxy plunged through the gas-rich disc of the galaxy about 3×10^8 yr ago. The Chandra image reveals more than 20 ULXs (defined as $L_{0.5-10\text{keV}} \gtrsim 3 \times 10^{39} \text{ erg s}^{-1}$). Most of these (about 80% of the entire X-ray emission from the galaxy) are in the dominant star-forming sites located precisely in the southern quadrant of the ring. Each source is brighter ($L_{0.5-10\text{keV}} \gtrsim 6 \times 10^{39} \text{ erg s}^{-1}$) than the most luminous ULXs seen in the Antennae. The lack of radial spread in these source positions, together with the known expansion velocity of the ring, show that these ULXs must have ages $\lesssim 10^7$ yr (Gao et al., 2003).

These observations clearly place very tight constraints on models for ULXs. I examine these below.

2 ULXS AND STAR FORMATION

King et al. (2001) examined the statistics of ULX formation, independently of the adopted model. If n is the number of currently-observed ULXs in some region of a galaxy, they showed first that the total number of potentially active ULXs in this region is actually

$$N = \frac{n}{bd} \quad (1)$$

where $b \leq 1$ is the beaming (radiation anisotropy) factor, and $d \leq 1$ the duty cycle. If for example $bd \ll 1$, most ULXs would either be radiating in directions away from our line of sight, or currently in low states. In the Cartwheel we can say more: the dearth of observed ULXs inside the expanding star-forming ring means that most have now ‘died’, i.e. ceased accreting. The total number of dead ULXs inside the ring is thus

$$N_{\text{tot}} = N \frac{t_*}{t_{\text{life}}} = \frac{n}{bd} \frac{t_*}{t_{\text{life}}} \gtrsim \frac{300}{bd} \quad (2)$$

where $t_* \simeq 3 \times 10^8$ yr is the time since the wave of star formation began to propagate outwards, $t_{\text{life}} \lesssim 10^7$ yr is the ULX lifetime in the ring, and I have used eq. (1) with $n \sim 10$. This estimate could be still larger if as usual, the gas surface density in the pre-intrusion galaxy increased exponentially towards the dynamical centre.

Second, King et al. (2001) showed that the mass-transfer lifetime of a ULX is

$$\tau = 10^6 \frac{m_2 a}{bd L_{40}} \text{ yr.} \quad (3)$$

Here m_2 is the initial mass (in M_\odot) of the reservoir from which the compact object accretes, $a \leq 1$ is the acceptance rate, i.e. the fraction of transferred reservoir mass actually gained by the accretor, and L_{40} is the apparent (isotropic) bolometric luminosity of the ULX in units of $10^{40} \text{ erg s}^{-1}$. Dividing (3) into (1) gives the important result that the required birthrate of ULXs is independent of both anisotropy b and duty cycle d (King et al., 2001). The Cartwheel observations now imply a further pair of constraints. Clearly, one of these is that the mass-transfer lifetime must be smaller than the inferred ULX lifetime, i.e. $\tau < t_{\text{life}}$. Using (3) this gives

$$m_2 < 10 \frac{bd}{a} L_{40}. \quad (4)$$

If the mass reservoir for the ULX is a binary companion star, we must also require that its main-sequence lifetime is less than t_{life} . Otherwise ULXs with initially wide separations would start mass transfer only long after the wave of star formation had passed. This would lead to a roughly uniform distribution of ULXs inside the ring, quite unlike the sharp concentration at the ring edge actually observed. This constraint translates directly into a limit on the initial companion mass

$$m_2 \gtrsim 15 \quad (5)$$

e.g. Iben (1967). With (4) this gives

$$a < 0.6bdL_{40} \quad (6)$$

This inequality must be satisfied by a comfortable margin to avoid the requirement that all ULXs should form with a narrow range of companion masses near $15M_\odot$. We can now apply the constraints (2, 5 6) to the two types of models for ULXs.

2.1 Stellar-mass ULXs

If the ULXs in the Cartwheel are stellar-mass binaries obeying the Eddington limit we must have $b \lesssim 0.1$. Constraint (5) tells us that these systems must be HMXBs, as expected. This probably means that $d \sim 1$, so that (2) implies

$$N_{\text{tot}} \gtrsim 3000. \quad (7)$$

This is quite reasonable for a population of HMXBs. Finally (6) gives

$$a \lesssim 0.06, \quad (8)$$

i.e. the accretion process must be very inefficient, with most of the mass lost by the companion failing to accrete on to the compact object. This requirement is easily satisfied for thermal-timescale mass transfer: the mass-loss rate from the companion is $-\dot{M}_2 \sim M_2/t_{\text{KH}} \gtrsim 10^{-5} M_\odot \text{ yr}^{-1}$, giving $a \lesssim 0.01$ for a $10M_\odot$ black hole accretor if the Eddington limit applies.

2.2 Intermediate-mass black hole ULXs

If the Cartwheel ULXs contain IMBHs accreting from massive stars we get a different set of constraints. Even without any assumptions about radiation anisotropy or duty cycle, (2) requires at least $N_{\text{tot}} = 300$ inactive IMBH within the star-forming ring. However Kalogera et al (2003; see also King et al., 2001) show that all such IMBH binaries are likely to be transient, with accretion discs subject to the standard thermal-viscous instability. This by definition means that the duty cycle $d < 1$. Disc theory does not yet provide quantitative estimates of d ; however observed disc-unstable systems have $d \lesssim 10^{-2}$, and there is considerable observational evidence (Ritter & King, 2001) to suggest that long-period systems with large discs, as in these ULXs binaries, have even smaller duty cycles $d \lesssim 10^{-2} - 10^{-3}$. We thus get from (2) the constraint

$$N_{\text{tot}} \gtrsim \frac{3 \times 10^4}{bd_{-2}} \quad (9)$$

where d_{-2} is d in units of 10^{-2} . From (6) we get

$$a < 6 \times 10^{-3} b d_{-2}. \quad (10)$$

3 DISCUSSION

I have considered explanations of the ULXs of the Cartwheel in terms of stellar-mass and IMBH binaries. Subsection 2.1 suggests that a population of high-mass X-ray binaries offers a reasonable picture. These systems must accrete at super-Eddington rates, as expected in the thermal-timescale mass transfer phase. These rates in turn suggest possible lines of explanation for the high apparent luminosities. The accretors in these HMXB binaries must be black holes with typical masses $M_1 \gtrsim 10M_\odot$, as Roche lobe overflow is dynamically rather than thermally unstable for initial mass ratios M_1/M_2 below some critical value (Webbink, 1977; Hjellming, 1989) which is probably of order 0.5 for the massive donors ($M_2 \gtrsim 15M_\odot$) in these HMXBs. (Dynamical-timescale mass transfer is ruled out as it would extinguish the binaries as X-ray sources.) Black hole accretors with $M_1 \gtrsim 10M_\odot$ also satisfy the constraint that their progenitors must have lifetimes $\lesssim 10^7$ yr, whereas this is probably not true of neutron stars for example.

Explanations of the Cartwheel ULXs invoking IMBHs accreting from massive stars run into problems. The required production rate $\sim 10^{-6} \text{ yr}^{-1}$ of IMBH implies a minimum total N_{tot} of $\gtrsim 300$, or more probably $\gtrsim 3 \times 10^4$, within the star-forming ring. Each of these IMBH must have found a stellar partner of $\gtrsim 15M_\odot$. If this process has efficiency $\eta < 1$ the above estimates of N_{tot} increase by factors η^{-1} , i.e. to $N_{\text{tot}} \gtrsim 3 \times 10^4 \eta^{-1}$. Models of IMBH formation in clusters (Miller & Hamilton, 2002; Gürkan, Freitag & Rasio, 2003) predict that only one IMBH is produced by a typical cluster mass of $3 \times 10^5 M_\odot$. Hence if all the ULXs in the Cartwheel are assumed to be IMBH this requires a mass $\gtrsim 10^{10} \eta^{-1} M_\odot$ to have appeared in star clusters since the intrusion event, which seems unlikely. Finally it appears that the accretion efficiency a must be low ($\lesssim 6 \times 10^{-3}$) for IMBH binaries. Of course this is not implausible for transient outbursts in which the accretion rate is very high; however it is perhaps disappointing to find super-Eddington accretion rates reappearing in a model specifically designed to exclude them.

Given these results, one should consider ways of rescuing the IMBH idea. There appear to be three main possibilities.

(a) Conditions at the current position of the star-forming ring may be highly unrepresentative of the region within it. This idea lacks plausibility, and would be completely ruled out if similar results are found in other galaxies.

(b) IMBH do not accrete from stars to make ULXs in starburst galaxies, but from some other kind of mass reservoir. There is no obvious candidate for this reservoir, and the constraints that accretion must occur at rates $\gtrsim 10^{-6} M_\odot \text{ yr}^{-1}$ and shut off after $\sim 10^7$ yr are severe.

(c) Most if not all of the ULXs found in regions of star formation are indeed HMXBs. However there is currently no clinching argument against a small minority containing IMBHs, as all the arguments presented here refer to population rather than individual source properties.

This last idea appears the most plausible. It is supported by the work of Grimm, Gilfanov & Sunyaev (2003),

who show that ULXs fit on to the X-ray luminosity functions of nearby star-forming galaxies when these are normalised by the star formation rate.

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